and

$$(E_y)_s = \frac{8\pi f^2 \exp(jx_r \sin\theta_a \cos\phi_a)}{(1+\cos\theta_0)(a+c)^2 c}\left\{jb\left[(a+2c)E_c(0)+cE_c\left(\frac{\pi}{c}\right)\right]\right.$$

$$\cdot J_1(x)\sin\phi_a + 2c\left[cE_c(0) - aE_c\left(\frac{\pi}{2}\right)\right]$$

$$\left.\cdot\sum_{n=0}^{\infty}(-j)^n\left(\frac{a-c}{a+c}\right)^{n/2} J_{n+2}(x)\sin(n+2)\phi_a\right\}. \tag{29}$$

From equations (5) and (7)

$$\left(\frac{a-c}{a+c}\right)^{\frac{1}{2}} = \tan\theta/2 \tan\theta_0/2. \tag{30}$$

For most antenna designs, equation (30) is much smaller than one, the series in equations (28) and (30) are, therefore, rapidly converging, and can in principle be evaluated to any desired accuracy.

It is noted that in the principal planes, these series can be related to Lommel functions of two variables[3].

The stimulating discussions with N. Amitay and E. R. Nagelberg are gratefully acknowledged by the author.

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Holographic Thin Film Couplers

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Recently P. K. Tien and his co-workers have described a prism coupler as a convenient means to feed light into a single mode of a guiding thin optical film.[1] Distributed couplers of this kind are of great interest for integrated optical devices. In this brief we describe thin

film coupling with a thick dielectric grating. To produce these grating couplers, we have used the materials and techniques of holography where dielectric gratings are known to yield high ($\gtrsim$ 90%) diffraction efficiencies.[2] Independently A. Ashkin and E. Ippen[3] suggested that a grating could be used as a thin film coupling device, and very recently M. L. Dakss, *et al.*,[4] have reported successful light coupling into thin films by means of a (thin) phase grating made of photoresist.

Figure 1 shows a grating coupler. A diffraction grating, placed in the vicinity of the guiding film, diffracts the incident light. If the diffracted wave is phase-matched to a mode of the film, then coupling occurs and light is fed into the film. The grating coupler is a distributed coupler just as the prism coupler, and much of the concepts and the theory developed for the latter[1] can be applied.

In order to make a good and efficient grating coupler one has to (*i*) use lossless and scatterfree materials, (*ii*) suppress unwanted grating orders, and (*iii*) provide for a sufficiently deep spatial modulation of the optical phase shift to achieve strong coupling and the associated short coupling lengths. Point (*i*) restricts us to phase or dielectric gratings. There are two possibilities to satisfy point (*ii*). The first is to use a thick grating and light incident near the Bragg angle. Then, Bragg effects will suppress all but one diffraction order. We shall call this coupler type a "Bragg coupler". The second possibility is to use a grating with a very large number of lines (or fringes) per millimeter. This results in such a large diffraction angle that only one diffraction order can propagate while all the others are beyond cutoff. This large diffraction angle leads to a thin film mode which travels in a direction reverse to that of the incident light, which is why we shall call this coupler a "reverse coupler." In many of the holographic materials which are available today, the achievable refractive index changes are relatively small (10^{-5} to 10^{-2}). It is, therefore, easier to satisfy point (*iii*) by using a Bragg coupler, where the phase shift accumulates throughout the thickness of the grating. The resulting strong coupling leads to short coupling lengths. These are desirable for miniaturization, and they make it easier to maintain the tolerances which are needed for phase-matching.

Figure 1 shows the geometry of a grating coupler, the choice of the coordinate system, and several parameters of interest. In our case the dielectric grating is formed in a layer of gelatin of refractive index n_g which is deposited directly onto the guiding film of index $n_f > n_g$. The grating is characterized by the grating vector $\mathbf{K}$ which is oriented perpendicular to the fringe planes and has a magnitude

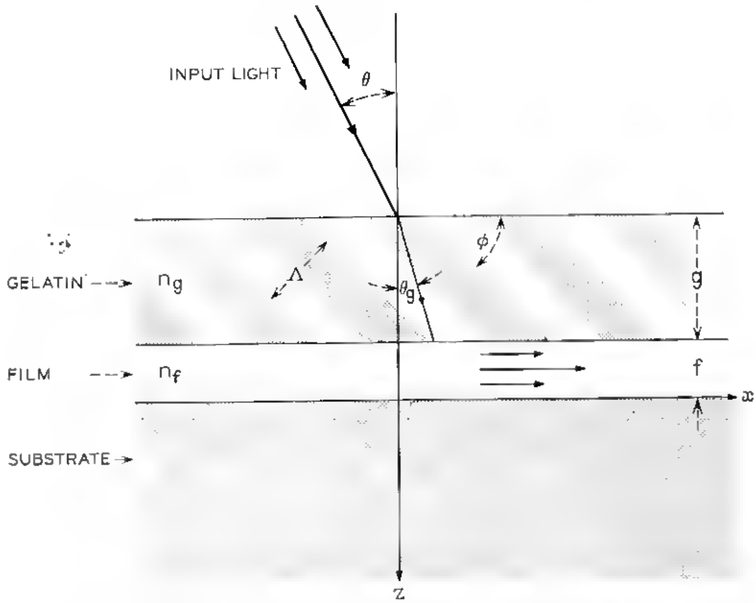

Fig. 1—Cross section of a grating coupler. Λ is the fringe spacing, ϕ the slant angle, and θ the angle of incidence. A transmission grating is shown. For a reflection grating the light is incident from the substrate side.

$$K = 2\pi/\Lambda \tag{1}$$

where Λ is the fringe spacing. The fringes are slanted with respect to the grating surface by an angle ϕ. The propagation vector of the incident light is $\mathbf{k}_{in}$ and has a magnitude equal to the free space propagation constant $k_0 = 2\pi/\lambda$. In the gelatin the k-vector of this light is $\mathbf{k}_g$ which is of magnitude $n_g k_0$.

The diffracted wave has a k-vector equal to $(\mathbf{k}_g + \mathbf{K})$. It is phase-matched to a film mode when this k-vector has a tangential ($x-$) component equal to the propagation constant β of the film mode, i.e., when

$$\beta = (\mathbf{k}_g + \mathbf{K})_x = (\mathbf{k}_{in} + \mathbf{K})_x . \tag{2}$$

Figure 2 shows the k-vector diagrams for the Bragg coupler (a) and the reverse coupler (b). The latter is shown for reasons of comparison. Note that in this latter case the grating vector $\mathbf{K}$ is parallel to the x-axis (which is typical for a thin grating). The cross marks the k-vector of the -1 order which is generated beyond cutoff. The circles of radius

$n_g k_0$ and k_0 respectively indicate the locus of the k-vectors of the input light in the gelatin and in air for a variahle angle of incidence. The line spaced a distance $\beta > n_g k_0$ away from the z-axis is the matching line. Phase-matching occurs when the vector sum $(\mathbf{k}_g + \mathbf{K})$ terminates on this line, as shown in the figure. The Bragg condition is obeyed when

$$\cos(\phi - \theta_g) = K/2n_g k_0 \tag{3}$$

where θ_g is the angle of incidence in the gelatin. Geometrically this implies that the vector sum $(\mathbf{k}_g + \mathbf{K})$ would terminate on the $n_g k_0$-circle.

It is clear from Fig. 2a that the Bragg condition and the phase-match condition cannot he met for the same angle of incidence. One can show that there is a minimum possihle difference $\Delta\theta_{g\,\mathrm{min}}$ between the Bragg angle and the matching angle which is approximately given by

$$\Delta\theta_{g\,\mathrm{min}} \approx (n_f - n_g)/n_g \tag{4}$$

where we have assumed that this "detuning angle" is small and that $\beta \approx n_f k_0$. The detuning angle is typically a few degrees of arc. The angular width $2\Delta\theta_{g\,\mathrm{Bragg}}$ of the Bragg response between half-power points is[2]

$$2\Delta\theta_{g\,\mathrm{Bragg}} = \Lambda/g \tag{5a}$$

for transmission gratings, and

$$2\Delta\theta_{g\,\mathrm{Bragg}} = (\Lambda/g)\cot\theta_g \tag{5h}$$

for reflection gratings, where g is the grating thickness. These formulas

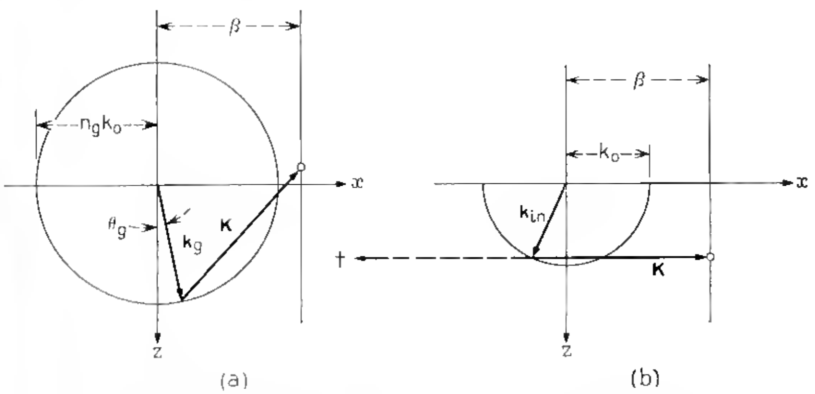

Fig. 2—k-vector diagrams for a Bragg coupler (a) and a reverse coupler (b). **K** is the grating vector; β, the propagation constant of a film mode.

assume unslanted gratings. Formulas are available also for slanted gratings[2], and one expects widtbs of the order of Λ/g, whicb is typically a few degrees. To take advantage of Bragg effects, we have to bring the matcbing angle as close as possible to the Bragg angle, and at least onto tbe wings of tbe Bragg response. Then we can expect suppression of unwanted orders and sufficiently strong coupling, whicb is, indeed, wbat we have observed experimentally.

Our experiments were done with Bragg couplers. We made the dielectric gratings in dichromated gelatin using tbe preparation and development techniques described in Ref. 5. Gelatin layers of about 4 μm thickness were deposited on the guiding films using a dipcoating tecbnique. The films were low-loss sputtered films of Corning 7059 glass which were kindly supplied by J. E. Goell and D. R. Standley.[6] They were about 0.3 μm thick and had a refractive index of $n_f = 1.62$.

We designed the couplers for light of wavelength $\lambda = 0.6328$ μm, incident perpendicular to the film plane. This prescribes gratings with a slant angle ϕ of about 45° and a fringe spacing of $\Lambda = 0.25$ μm (i.e., 4000 lines/mm). To obtain the rigbt grating parameters, some experimentation is necessary because the gelatin shrinks during development. We produced tbe desired fringe pattern holographically by exposing the sensitized gelatin at the shorter wavelength of $\lambda' = 0.4416$ μm, which is a line of the cadmium laser. The k-vector diagram of Fig. 3 indicates bow the use of this sborter wavelength gives us fringes with the wanted k-vector at convenient angles of incidence. To get the proper interference angles in the gelatin, the two collimated light beams

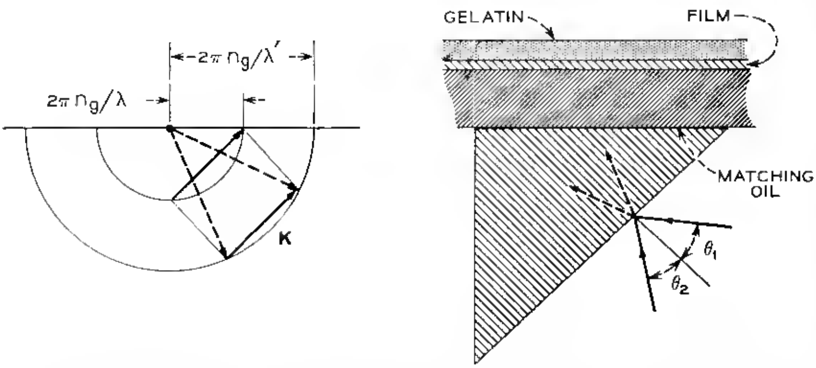

Fig. 3—Arrangement for holographic exposure used to make the grating coupler. The k-vector diagram shows how the grating vector **K** is conveniently produced by the interference of blue light (λ').

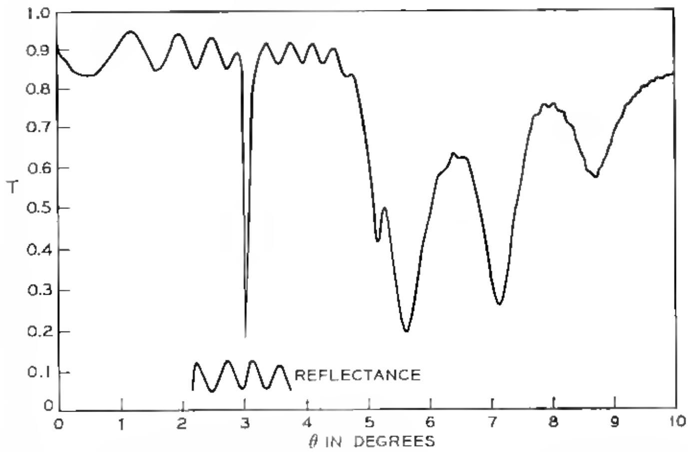

Fig. 4—Angular transmission spectrum for $2w_0 = 0.3$ mm. T is the transmittance of the coupler and θ the angle of incidence (in air). Light is incident from the substrate side.

were entered through a 45° prism which was joined to the film substrate with matching oil as shown in the figure. The angles of incidence on the prism were approximately $\theta_1 = 55°$ and $\theta_2 = 50°$. The edge of the coupler was produced by the shadow of a knife edge in one of the exposing beams about 5 cm away from the gelatin. The size of the resulting gratings was approximately 5 mm × 5 mm.

We made several Bragg couplers and studied their characteristics at 0.6328 μm. We obtained coupling both on transmission and on reflection from the grating, but the better results (which we report below) were obtained with reflecting couplers, i.e., with light incident from the substrate side. We used a gaussian laser beam with its waist positioned near the grating. The beam was positioned at the edge of the coupler. To optimize the coupling further, we varied the waist diameter $2w_0$ and the spacing between the coupler and the waist. For our best coupler we found optimum coupling in a diverging beam with a waist diameter of about $2w_0 = 0.3$ mm and a waist-coupler spacing of 16 cm. For this case the beam diameter at the coupler was $2w = 0.6$ mm. By analyzing the m-lines[1] we found a value for the optimum coupling length which was of the same magnitude. The m-lines also indicated that our film guide supported only one TE and one TM mode.

Figure 4 shows the angular transmission spectrum obtained for TE-coupling with the optimum beam parameters. This plot is obtained

by monitoring the transmittance T through the substrate-film-gelatin sandwich for a variable angle of incidence θ. In the figure we notice a small modulation ($\Delta T \approx 0.1$) superimposed on the spectrum which is due to substrate resonances. The large dip near $\theta = 3°$ is caused by coupling into the film. The angular width of this dip is about 0.1°. The Bragg condition is obeyed near $\theta = 6°$. The Bragg response is strongly modulated by gelatin and film resonances. It has an overall width of about 3°. The measured reflectance of the coupler is also shown in the figure. From these data we arrived at the following power balance for optimum coupling: 3 percent of the incident light is absorbed in the substrate, film and gelatin, 8 percent reflected, 18 percent transmitted, and 71 percent coupled into the film.

Coupling to the TM film mode is relatively weaker for the above coupler because it was designed for normal incidence ($\theta \approx 0$) where TM diffraction is at a minimum.[2] The same beam parameters which produced optimum TE-coupling yielded TM-coupling of only 15 percent.

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